

# Frequency and spectrum analysis of $\gamma$ Doradus type *Kepler* target KIC 6462033

C. Ulusoy<sup>a,\*</sup>, I. Stateva<sup>b</sup>, I. Kh. Iliev<sup>b</sup>, B. Ulaş<sup>c</sup>

<sup>a</sup>*College of Graduate Studies, University of South Africa, PO Box 392, Unisa, 0003, Pretoria, South Africa*

<sup>b</sup>*Institute of Astronomy with NAO, Bulgarian Academy of Sciences, blvd. Tsarigradsko chaussee 72, Sofia 1784, Bulgaria*

<sup>c</sup>*Izmir Turk College Planetarium, 8019/21 sok., No: 22, İzmir, Turkey*

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## Abstract

We present results of an asteroseismic study on the  $\gamma$  Dor type *Kepler* target KIC 6462033. *Kepler* photometry is used to derive the frequency content and principal modes. High-dispersion ground-based spectroscopy is also carried out in order to determine the atmospheric parameters and projected rotational velocity. From an analysis of the *Kepler* long cadence time series, we find that the light curve of KIC 6462033 is dominated by three modes with frequencies  $f_1=0.92527$ ,  $f_2=2.03656$  and  $f_3=1.42972$  d<sup>-1</sup> as well as we detect more than a few hundreds of combination terms. However, two other independent frequencies appear to have lower amplitudes in addition to these three dominant terms. No significant peaks are detected in the region  $> 5$  d<sup>-1</sup>. We therefore confirm that KIC 6462033 pulsates in the frequency range of  $\gamma$  Dor type variables, and a future study will allow us to investigate modal behaviour in this star.

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\*Corresponding author. Tel.: +27792420624; Fax: +274294672  
E-mail address: tulusoc@unisa.ac.za

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## 1. Introduction

The  $\gamma$  Dor stars have been known as a class of pulsating late A and F type variables for more than two decades. After the variability of the prototype,  $\gamma$  Doradus, was discovered by Cousins & Warren (1963) they were first named and classified as a new group of pulsating stars by Balona, Krisciunas & Cousins (1994) and Kaye et al. (1999), respectively. Their oscillations are characterized by high-order, low-degree and multiple non-radial  $g$ -modes with periods of 0.3 to 3 d (Kaye et al., 1999; Balona et al., 2011).

Since they have both convective cores and convective envelopes driving is assumed to be operated by a convective flux-blocking mechanism at the base of their convective envelope where radiative damping occurs in the  $g$ -mode cavity (Guzik et al., 2000; Dupret et al., 2004, 2005; Grigahcène et al., 2010). Moreover, the depth of the convective envelope is play an important role to drive  $g$ -mode pulsations in  $\gamma$  Dor stars, and the driving mechanism becomes efficient when the position of convective envelope makes the thermal relaxation time comparable to  $g$ -mode periods (Dupret et al., 2004; Grigahcène et al., 2010; Balona et al., 2011). These stars are located in a region on/or near the main sequence (with masses of 1.5 to 1.8  $M_{\odot}$  (Aerts, Christensen-Dalsgaard & Kurtz , 2010)) that partially overlaps with the red edge of  $\delta$  Sct instability strip in the Hertzsprung-Russell diagram (HRD). In this case, they are expected to show both  $p$ - and  $g$ -mode hybrid pulsations in their frequency spectra. From the ground-based observations

$\gamma$  Dor/  $\delta$  Sct hybrid pulsations were first found by Handler et al. (2002). Following that, a few hybrid type pulsator candidates were reported by several authors (Henry & Fekel, 2005; Rowe et al., 2006; King et al., 2007). By using *Kepler* data, Grigahcène et al. (2010) have recently proposed a new observational classification scheme for the pulsators located in this overlapping region.

In particular, new generation space missions such as *Kepler* (Borucki et al., 2010), *CoRoT* (Baglin et al., 2006) and *MOST* (Walker et al., 2003) allow us to detect further hybrid candidates with very low-amplitude pulsation modes which may challenge our understanding of their unique pulsation mechanism (Hareter et al., 2010; Uytterhoeven et al., 2011; Tkachenko et al., 2013).

The star KIC 6462033 (TYC 3144-646-1,  $V = 10.83$ ,  $P = 0.69686$  d) has been monitored by the *Kepler* satellite in short-cadence (SC, 1-min exposures, Gilliland et al. (2010)) and long cadence (LC, 29.4-min exposures, Jenkins et al. (2010)) modes, and was firstly classified as a  $\gamma$  Dor-type star by Uytterhoeven et al. (2011).

In this paper, we present results of a frequency analysis of the *Kepler* LC dataset to investigate pulsational frequencies as well as an analysis of ground-based spectra. *Kepler* observations and data processing procedure and the frequency analysis are described in Section 2. Section 3 deals with the derivation of the fundamental stellar parameters from the ground-based spectroscopy. Conclusions are briefly discussed in Section 4.

## 2. The *Kepler* Photometry

*Kepler* data were used to investigate the frequency content of KIC 6462033

Table 1: Frequencies, amplitudes ( $A$ ), phases ( $\phi$ ) and  $S/N$  for the combined (LC) Q0-Q16 data set of KIC 6462033. Uncertainties are presented in paranthesis.

ID	$f(\text{d}^{-1})$	$A(\text{mmag})$	$\phi$ (radians)	$S/N$
$f_1$	0.92527(2)	0.821(19)	5.785(11)	74
$f_2$	1.42972(2)	0.696(16)	4.248(11)	76
$f_3$	2.03656(2)	0.583(17)	2.888(14)	58
$f_4$	1.02317(2)	0.523(13)	3.707(11)	70
$f_5$	3.43850(2)	0.481(12)	5.382(11)	71
$f_6 \approx 2f_4$	2.04634(3)	0.261(9)	4.232(17)	48
$f_7 \approx 3f_4$	3.06955(9)	0.028(3)	4.745(59)	14
$f_8 \approx 2f_1$	1.85030(15)	0.023(5)	4.570(103)	8
$f_9 \approx 2f_5$	6.87700(13)	0.015(3)	3.849(87)	9
$f_{10} \approx 4f_4$	4.09270(12)	0.014(3)	1.499(82)	10
$f_{11} \approx f_2 - f_1$	0.50377(13)	0.061(12)	1.701 89)	9
$f_{12} \approx f_2 + f_1$	2.35493(7)	0.032(3)	1.290 48)	17

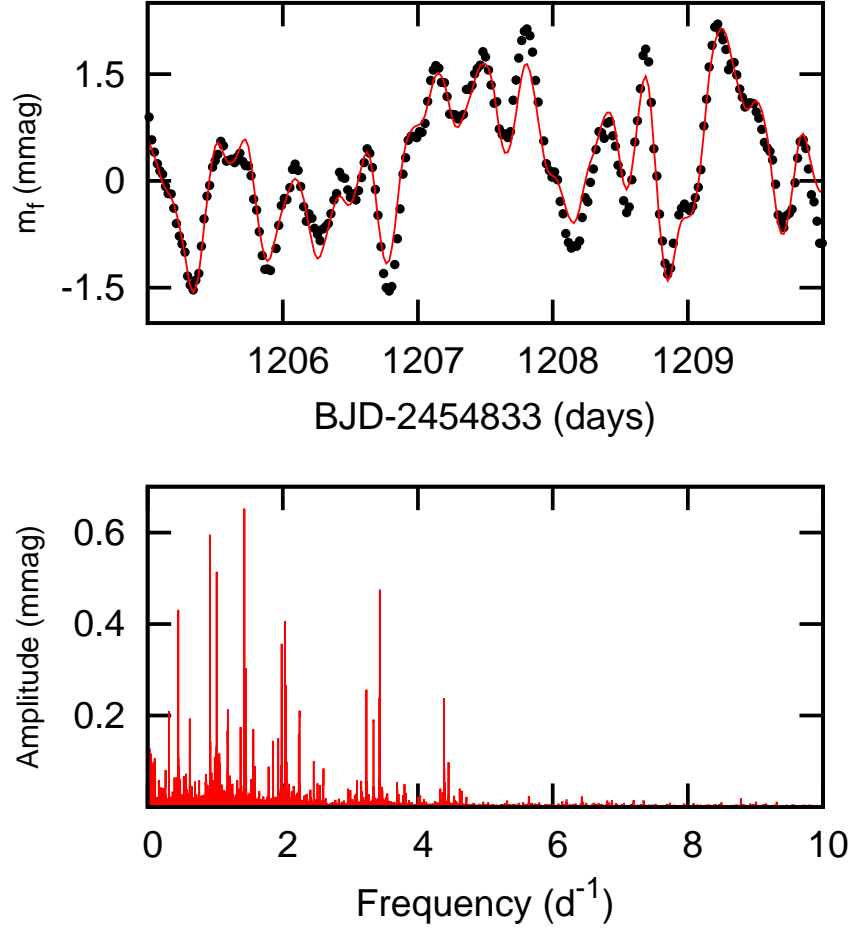


Figure 1: A sample of the *Kepler* light curve covering 5d of the original data (top) and amplitude spectrum (bottom) of KIC 6462033.

The *Kepler* satellite<sup>1</sup> was launched on 2009 March 6 primarily aimed to detect terrestrial and larger planets in the solar neighbourhood by the transit method (Borucki et al., 2010; Koch et al., 2010). *Kepler* has continuously observed the brightnesses of over 100000 stars in a 105 square degree fixed field for at least 3.5 years. The uninterrupted time series photometry which makes the data ideal for seismic studies has been successful to determine a very large number of pulsation modes of high accuracy.

KIC 6462033 was observed with 1- min exposures from BJD 2455156.5156 to BJD 2455182.5060 in SC mode (only Q3.3) and BJD 2454953.5285 to BJD 2455990.9688 in LC modes (Q0-Q16) for a total of 102633 data points. Since most of the observations were obtained in LC mode and SC data frequencies are of limited value (about  $700 \text{ d}^{-1}$ ) we decided to analyze the LC data collected between the *Kepler* commissioning quarters Q0 and Q16. In order to perform frequency analysis, the data were first cotrended the simple aperture Photometry (SAP) fluxes by using cotrending basis vector (CBV) files and `kepcotrend` task of PyKE package (Still & Barclay, 2012). After removal of instrumental systematics from the light curve, final magnitudes were obtained following the formula  $m_i = -2.5 \log F_i$ , where  $m_i$  refers the magnitude and  $F_i$  is the raw SAP flux. We obtained final magnitude ( $m_f$ ) values by subtracting the  $m_i$  magnitudes from their fitting polynomial.

`SigSpec` code (Reegen, 2007) was used for frequency extraction of KIC 6462033. The program assigns the spectral significance levels for the discrete Fourier transform (DFT) amplitude spectra of time series at randomly time

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<sup>1</sup><http://kepler.nasa.gov/>

sampling by the fitting formula:

$$f(t) = \sum_i^n A_i \cos(2\pi ft - \phi_i) \quad (1)$$

where  $A_i$  is the amplitude of corresponding frequency,  $f$  is the frequency value, and phase angle  $\phi_i$ .

The probability density function (PDF) of a given DFT amplitude level is determined analytically and false-alarm probability refers to the spectral significance for a certain frequency. The default significance threshold in **SigSpec** is set at 4.1784 that theoretically corresponds to  $S/N = 3.5$  (Reegen, 2007; Breger et al., 2011). The theoretical Rayleigh resolution is  $1/T = 0.000696 \text{ d}^{-1}$ . Although  $\gamma$  Dor-type oscillation frequencies are typically detected in the range of  $0\text{-}5 \text{ d}^{-1}$  (Balona et al., 2011) our computations are limited in the range  $0 \text{ d}^{-1}\text{-}10 \text{ d}^{-1}$  to search for frequencies in the region  $> 5 \text{ d}^{-1}$ .

The frequency analysis yielded five independent frequencies, several hundreds of combination terms and harmonics up to  $2f_5$ . Using SC time series, the first three peaks of high-amplitude were previously reported by Ulusoy et al. (2013). We also confirm that the light variation is dominated with three frequencies  $f_1=0.92527$ ,  $f_2=2.03656$  and  $f_3=1.42972 \text{ d}^{-1}$ . However, the LC data allowed us to detect two other independent terms of much lower amplitude,  $f_4=1.02317$ , and  $f_5=3.43850 \text{ d}^{-1}$ . The lowest frequency that appears significant is  $f_2-f_1=0.50377 \text{ d}^{-1}$ . On the other hand, the term with the lowest amplitude is detected to be significant in the region around  $2 \text{ d}^{-1}$ . The resulting frequencies of KIC 6462033 are listed in Table 1, together with their amplitudes, phases and  $S/N$  values and uncertainties.

### 3. Spectroscopy

The CCD spectra were used for determination of the atmospheric parameters of KIC 6462033 and the projection of the rotational velocity  $v \sin i$ . They were obtained with the 2m RCC telescope of the Bulgarian National Astronomical Observatory - Rozhen in three spectral regions: 6510–6610 Å, 4810–4910 Å and 4460–4560 Å. The regions were focused on H $\alpha$ , H $\beta$ , Mg II  $\lambda$  4481 Å lines. The Photometrics AT200 camera with a SITe SI003AB 1024  $\times$  1024 CCD chip, (24  $\mu$ m pixels) was used in the third camera of the Coudé spectrograph to provide spectra with a typical resolution  $R = 32\,000$  and S/N ratio of about 40. The instrumental profile was checked by using the comparison spectrum so that its FWHM was about 0.2 Å. IRAF standard procedures were used for bias subtracting, flat-fielding and wavelength calibration. The final spectra were corrected to the heliocentric wavelengths.

Model atmospheres were calculated under **ATLAS 12** code. The **VALD** atomic line database (Kupka et al. 1999), which also contains Kurucz (1993) data, was used to create a line list for the synthetic spectra.

The synthetic spectra were obtained by using the code **SYNSPEC** (Hubeny, Lanz & Jeffery 1994, Krтіčka 1998). We accepted the microturbulence to be 2 km s $^{-1}$ . The computed spectra were convolved with the instrumental profile by a Gaussian of 0.2 Å FWHM and rotationally broadened to fit the observed spectra.

The best fit of H $\beta$  and H $\alpha$  was obtained for the atmosphere model with  $T_{\text{eff}} = 7150$  K,  $\log g = 4.3$ . We used Mg II  $\lambda$  4481 Å line for the determination of the projected rotational velocity. The match between the synthetic and observed profile gave as a result  $v \sin i = 90$  km s $^{-1}$ . In Fig. 2 it can be seen the best fit of H $\beta$  and the fit with the model given by **Kepler** Input



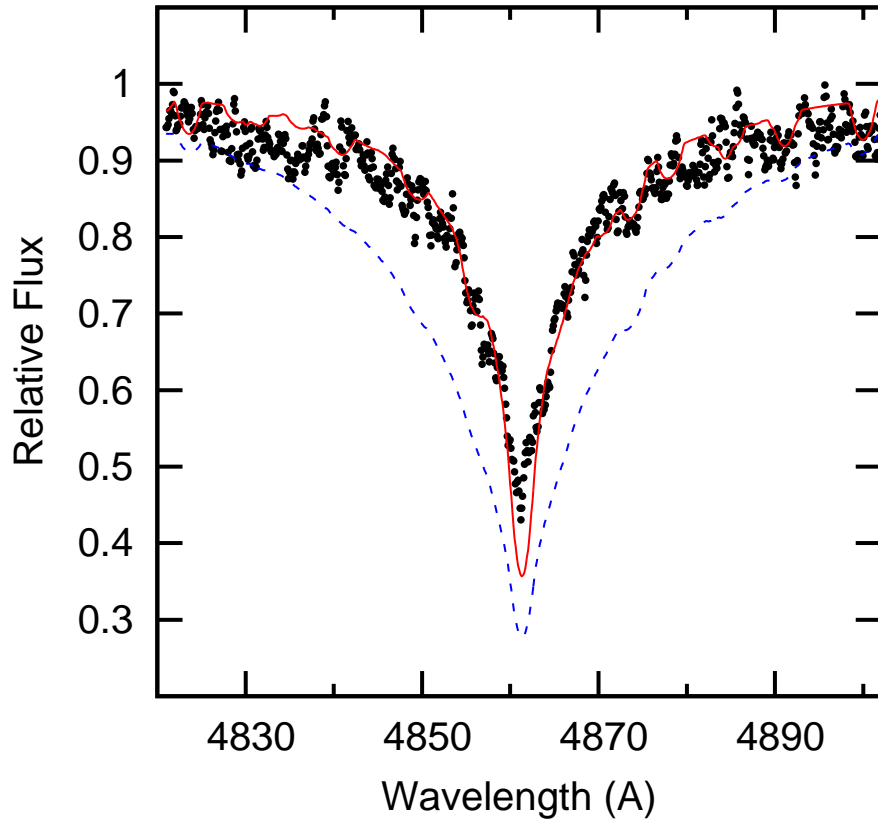


Figure 2:  $H\beta$  line (dots) fitted with a model with  $T_{\text{eff}} = 7150$  K,  $\log g = 4.3$  (solid line). The model proposed by KIC -  $T_{\text{eff}} = 8390$  K,  $\log g = 4.3$  is given by dashed line.

Catalogue (hereafter KIC) (Uytterhoeven et al., 2011). The values given by KIC -  $T_{\text{eff}} = 8390$  K,  $\log g = 4.3$  differ from our results concerning the temperature but it is not surprisingly. As Tkachenko et al. (2012) mentioned in their spectroscopic work on  $\gamma$  Doradus stars the spectroscopically derived temperatures in some cases disagreed with the KIC values.

#### 4. Conclusions

We have presented both frequency and first spectrum analysis of the  $\gamma$  Doradus star KIC 6462033 observed by the *Kepler* satellite. In order to extract frequencies from the LC *Kepler* data, the frequency analysis was performed using the software package **SigSpec** (Reegen, 2007). Our results are in a good agreement with previous analyses of the SC *Kepler* data (Ulusoy et al., 2013). We confirm that the light curve of KIC 6462033 is dominated by three modes with frequencies  $f_1 = 0.92527$ ,  $f_2 = 2.03656$ ,  $f_3 = 1.42972$  d<sup>-1</sup>. Besides these three modes, two additional frequencies which have much lower amplitudes are detected:  $f_4 = 1.02317$ , and  $f_5 = 3.43850$  d<sup>-1</sup> together with their harmonics and combination terms. No significant peaks are appeared in the region  $> 5$  d<sup>-1</sup>. As a result, KIC 6462033 pulsates in the frequency range ( $\leq 5$  d<sup>-1</sup>) of  $\gamma$  Dor type variables (Grigahcène et al., 2010).

Since ground-based spectroscopy is needed to complete the obtained results by using *Kepler* photometry, we also carried out high dispersion spectroscopic observations to derive the fundamental parameters and projected rotational velocity for KIC 6462033. By fitting the Balmer line profiles and Mg II  $\lambda 4481$  Å line between the synthetic and observed spectra we obtained  $T_{\text{eff}} = 7150$  K,  $\log g = 4.3$ ,  $v_{\text{mic}} = 2$  km s<sup>-1</sup> and  $v \sin i = 90$  km s<sup>-1</sup> respec-

tively. We find that the values of effective temperature and surface gravity listed in the KIC are not overlapped with the ones derived from our ground-based spectra.

In  $\gamma$  Dor stars, spherical harmonic degrees ( $l$ ) and identification of the radial order ( $n$ ) of observed frequencies can be determined with frequency ratio method (FRM) (Moya et al., 2005; Suárez et al., 2005). This method was particularly developed for  $\gamma$  Dor variables that show at least three  $g$ -mode pulsation frequencies in the asymptotic regime. The method also provides an estimate of the integral of the Brunt-Väisälä frequency weighted over the stellar radius along the radiative zone if we assume that all excited modes in the star correspond to the same spherical harmonic degree  $l$  with  $m=0$ . However, it should be noted that the FRM is only applicable and reliable for objects with rotational velocities up to  $70 \text{ km s}^{-1}$  due to the effect of rotation on the observational Brunt-Väisälä frequency (Suárez et al., 2005). Considering that the rotational velocity of KIC 6462033 is over the limit of validity of the FRM we therefore didn't attempt mode identification for KIC 6462033 with FRM. In conclusion, we expect that more high-resolution spectroscopic observations may enable us to identify at least some of modes and our present work will support in future asteroseismic studies of this star.

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